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Spiral Structure in WZ Sagittae around the 2001 Outburst Maximum

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Abstract

Intermediate resolution phase-resolved spectra of WZ Sge were obtained on five consecutive nights (July 23 – 27) covering the initial stage of the 2001 superoutburst. Double-peaked emission lines of HeII at 4686 Å, which were absent on July 23, emerged on July 24 together with emission lines of CIII / NIII Bowen blend. Analyses of the HeII emission lines using the Doppler tomography revealed an asymmetric spiral structure on the accretion disk. This finding demonstrates that spiral shocks with a very short orbital period can arise during the initial stage of an outburst and may be present in all SU UMa stars.

Key words: accretion, accretion disks — stars: cataclysmic variables — stars: dwarf novae — stars: individual (WZ Sge)

1. Introduction

Dwarf novae are a subclass of cataclysmic variables (CVs), which are close binary systems consisting of a white dwarf and a red dwarf secondary, transferring matter via the Roche lobe overflow (for a recent review, see Warner 1995). Dwarf novae show frequent outburst, which are episodes of enhanced accretion through the disk onto the central object. These systems provide good test cases for various theories of accretion disk models.

WZ Sge is the prototype star of WZ Sge-type stars (originally proposed by Bailey 1979), which is a subclass of SU UMa-type dwarf novae. The remarkable outburst properties (a large amplitude ~ 8 mag., and the extremely long time interval between outbursts about 33 years) show that WZ Sge is the most extreme case among dwarf novae. WZ Sge has a very short orbital period of 1.37 h, and it is one of the few eclipsing dwarf novae, whose inclination angle of the orbital plane is known to be 75 ± 2 degrees (for the detailed model of WZ Sge, see Smak 1993).

One of the main long-standing problems concerning accretion disks is the mechanism of angular momentum transport. Spiral shocks have long been proposed as a possible mechanism for the transport (e.g. Sawada et al. 1986, Spruit 1987, Savonije et al. 1994). If the disk extends far enough in the Roche lobe, spiral shocks are excited by the tidal field of the secondary and result in the formation of two prominent spiral arms. The gas in the disk loses its angular momentum when it passes through the spiral shocks.

Analysis of the double-peaked emission lines using Doppler tomography is a well-established method for imaging the accretion disks in CVs (Marsh & Horne 1988). Emission lines seen in the spectra arise from the accretion disk and can be seen in a double-peaked shape as a result of Doppler motion of the disk within the binary. The velocity of the material in the disk determines the line profile.

Recently, spiral structures in the accretion disks of some dwarf novae during outbursts have been discovered, IP Peg (Steeghs et al. 1997, Harlaftis et al. 1999, Morales-Rueda et al. 2000), EX Dra (Joergens et al. 2000), and U Gem (Groot 2001). Their presence probed by the Doppler tomography method triggered a renewed interest in spiral shock models. The spiral pattern is interpreted as evidence for shock waves, which is consistent with the results of hydrodynamical simulations (e.g. Steeghs & Stehle 1999, Makita et al. 2000).

Aside from during outbursts, Skidmore et al. (2000) presented an extensive set of Doppler maps of WZ Sge in quiescence using both optical and infrared emission lines. In these maps, the accretion disk structure was found to be asymmetric and the bright spot region was shown to be extended along the mass transfer stream, but these structures didn't look like spirals.

The outburst of WZ Sge was discovered by an amateur astronomer on 2001 July 23.565 UT at a visual magnitude 9.7 (Ishioka et al. 2001a), having occurred 10 years earlier than the common expectation. Receiving the report of the outburst, we started time-series spectroscopic observations, to clarify the evolution of the accretion disk structure at the very beginning of the outburst.

Table 1. Log of observations.

UT (2001 July) (start – end)	Orbit covered	No. of spectra	Obs. mode	Observ-atory
23.736– 23.777	—	6	low	BAO
24.576– 24.701	2.2	52	—	OAO
25.592– 25.682	1.6	40	—	OAO
26.586– 26.664	1.4	22	—	OAO
26.539– 26.697	2.8	74	high	BAO
27.582– 27.673	1.6	25	—	OAO

2. Observation

The CCD spectroscopic observations were performed with the 91-cm telescope at Okayama Astrophysical Observatory (OAO) and the 101-cm telescope at Bisei Astronomical Observatory (BAO) between July 23 and 27. According to VSNET [1], WZ Sge was on the rising stage on July 23, and was at the maximum of this superoutburst on July 24.

The intermediate dispersion spectra at the OAO covering 3950-5100 Å with a resolution of 3000 were obtained using a CCD camera (Andor DU440 camera with 2048 × 512 pixels Marconi CCD). At the BAO, the low dispersion spectra covering 4250-6800 Å were obtained using a peltier-cooled CCD camera (Mutoh CV-16II with 1536 × 1024 pixles KAF-1600 CCD), while the high dispersion spectra covering 6390-6750 Å were obtained using a liquid-nitrogen-cooled CCD camera (AstroCam 4200 series with UV-coated 1024 × 256 pixels EEV CCD), resulting the resolution of 1500 and 15000 respectively. The journal of our observations is summarized in Table 1.

All of the raw frames were processed in the usual manner using IRAF. The raw spectrum images were bias-subtracted and flat-fielded, then stellar spectra were extracted from two dimensional spectrum images. Except for spectra taken on July 23, all spectra were normalized to the continuum level, by means of the spline fitting. The averaged signal to noise ratios (S/N) at the continuum level were 60-100 for OAO data using exposure times of 180-300 s, and 25-40 for BAO data using exposure times of 120 s respectively, which depend on the brightness of the object and the sky condition.

Barycentric corrections to the observed times were applied before the following analysis. We adopted the binary ephemeris: $T_0(BDJD) = 2437547.728868 + 0.05668784707 \times E$, where T_0 is the mid-point of the eclipse, and a phase offset $\phi_c = -0.022$, to convert the ephemeris to the inferior conjunction of the binary. Both of them are taken from Skidmore et al. (2000).

3. Result

Figure 1 is the flux-calibrated spectrum on July 23, which corresponds to the rising stage of the superoutburst. It shows Balmer lines, Hα and Hβ, in absorption on a blue continuum. HeI lines (4922 Å, 5876 Å, 6678 Å) are also seen in absorption. It is to be noted that no emission or absorption component around the wavelength of HeII and CIII / NIII complex was observed on July 23.

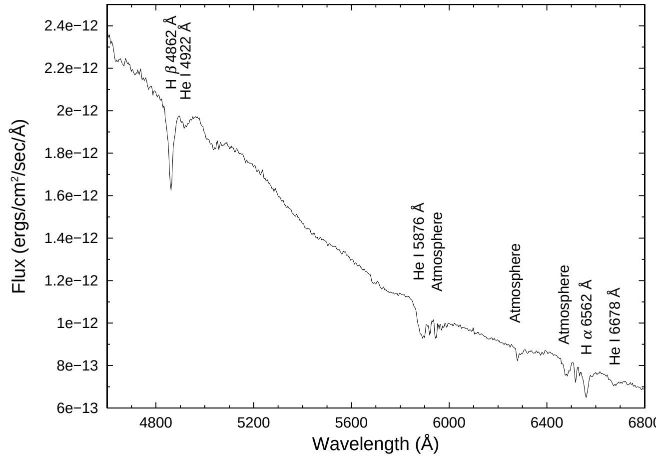

Fig. 1. The flux-calibrated spectrum on July 23, corresponding to the rising stage of the 2001 superoutburst of WZ Sge. Spectra taken on July 23 were corrected for instrumental response using the flux standard HD 8634.

Figure 2 shows the continuum-fitted spectra at four different orbital phases, where the changes of the line profiles are very impressive. The most remarkable features in the spectra on July 24 are the strong emission lines of the HeII 4686 Å and the CIII / NIII complex at 4640 Å with double-peaked profiles, both of which were not observed on July 23. The peak intensities and the separation between peaks vary with the orbital period. Hβ shows an emission component on the blue-wing between the phase 0.7 – 0.0, while it shows an emission component on the red-wing between the phase 0.3 – 0.5. Nearly the same behavior of Hβ is observed on July 25, 26 and 27. However, we notice that no emission component of Hβ was observed on July 23. According to Steeghs et al. (2001b), who obtained spectroscopic data on Aug. 6 and 13, prominent double-peaked emission components are seen at both Hα and Hβ, where the blue component is much stronger than the red component. Higher Balmer series Hγ and Hδ are observed as broad absorption features between July 23 – 27, together with neutral Helium lines such as 4388 Å, 4472 Å and 4922 Å. The line feature resembles that obtained at the beginning of the 1978 outburst reported in Patterson (1978) and in Ortolani el al. (1980), both of which are taken at four days after the maximum.

We constructed Doppler maps of WZ Sge using the time-resolved spectra with the IDL-based fast-maximum entropy package developed by Spruit (1998) [2]. Figure 3 shows the results for the strong emission line of HeII on July 24 and weak emission line of Hα which evolved on July 26. The HeII map displays the dominant accretion disk with extended spiral arms, which constitutes an

[1] http://www.kusastro.kyoto-u.ac.jp/vsnet/

[2] Available at http://www.mpa-garching.mpg.de/%7Ehenk/

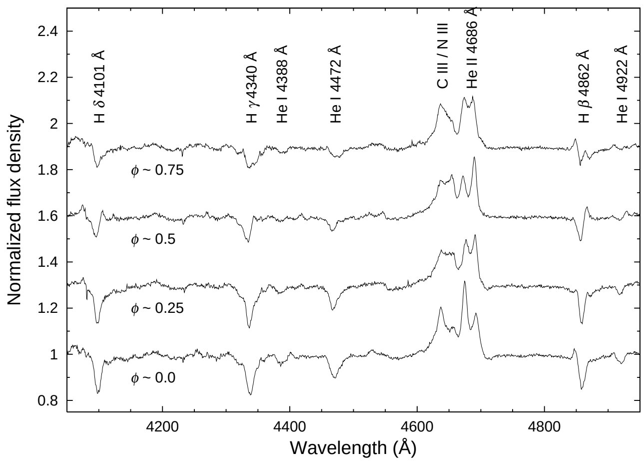

Fig. 2. Spectra of WZ Sge on July 24. The spectra are bound into four orbital phase slots. Before averaging, each spectra were shifted according to the radial velocity $K_1 \sin(\phi)$, with $K_1 = 37$ km s^{-1} (Steeghs et al. 2001b). An arbitrary offset were applied between spectra for display purpose.

asymmetric spiral structure. The spiral arm in the right quadrants extends about ~ 135 degrees, and is stronger than the arm in the opposite quadrants. There is no observed evidence for the irradiation of the secondary star nor for the hot-spot. The images look quite similar to the HeII map of EX Dra (Joergens et al. 2000), although the phase of the spirals seems to be different. In constast, the Hα image on July 26 significantly differs from the HeII maps. It looks almost flat and there is no remarkable feature such as the secondary star.

We clearly find an evidence for spiral structures in the accretion disk at the beginning of the outburst of WZ Sge. The Doppler maps of HeII on July 25, 26 and 27 are almost as same in strength and location as that on July 24. Steeghs et al. (2001a) also reported that the HeII and CIII emission lines were dominated by two-armed spiral pattern on July 28. Taking into account that no emission feature of HeII was detected on July 23 when the object was on the rising stage, the shocks stood immediately just after the maximum of the outburst, and persisted almost constant in strength and location during the early stage of the outburst.

4. Discussion

The strong emmisivity of HeII and almost no contibution of Hα indicate that the accretion disk had a high temperature of a few tens of thousands K even at the edge region at the early phase of this outburst. In addition, no evidence of the secondary in the HeII and Halpha indicates that the effect of irradiation on the secondary was relatively weak. This apparent lack of strong irradiation on the secondary may have been a result of the shielding of photons by a thickened accretion disk around the superoutburst maximum, which is a natural consequence of an extremely hot (a few tens of thousands K) disk.

All of the three systems in which spiral arms have been observed, i.e. IP Peg, EX Dra and U Gem, are the systems above the period gap. Harlaftis et al. (1999) suggested the possibility that the spiral shocks only develop in systems above the period gap, since higher mass-ratio binaries are expected to have a heavier secondary star which induces stronger tidal torques. Nevertheless, WZ Sge is the system below the period gap, together with other SU UMa-type stars. The present discovery suggests the possibility of the existence of spirals in other SU UMa-type stars during outburst, although there has been a report of nagative detection (e.g. OY Car in outburst (Harlaftis & Marsh 1996)). There may be a selection effect since the outburst of the short period systems are difficult to expect, and as a result, phase-resolved spectroscopy of the short period systems at the very beginning of outburst must be difficult. Further strategic observations are strongly encourged to confirm the speculation.

According to Ishioka et al. (2001a), the humps with the orbital period called "early superhumps" were observed at the very early stage of this superoutburst, which is the characteristics of WZ Sge-type stars. Even though the origin of "early superhumps" is still unknown, the immediate evolution of spirals suggests that the double peak of "early superhumps" may be understood as a reflection of the two arms of the spiral structure. If so, the extended wing in the right half region of HeII Doppler map corresponds to the secondary maxima of the early superhumps ($\phi \sim 0.2$), and the weak component in left quadrant of HeII Doppler map corresponds to the primary maxima of the early superhumps ($\phi \sim 0.6 - 0.7$). This intensity inversion is left to be a problem.

Although there is no observation of periodic modulation like "early superhumps" in the systems where spiral structures were detected, it may be possible that different mechanisms drive two-armed spiral patterns during outburst in WZ Sge and in some dwarf novae above the period gap. In a theoretical work, Lin & Papaloizou (1979) suggested that only an accretion disk in a small mass-ratio system (such as $q < 0.1$) could show a strong spiral dissipation pattern with the 2:1 Lindblad resonance. O'Donoghue (1990) pointed out that complex oscillations observed in AM CVn stars with more extremely low mass-ratios than WZ Sge may be understandable with multiple standing shocks demonstrated by Lin & Papaloizou (1986). We suppose that such mechanisms of standing shock of AM CVn stars may be applicable in the case of WZ Sge.

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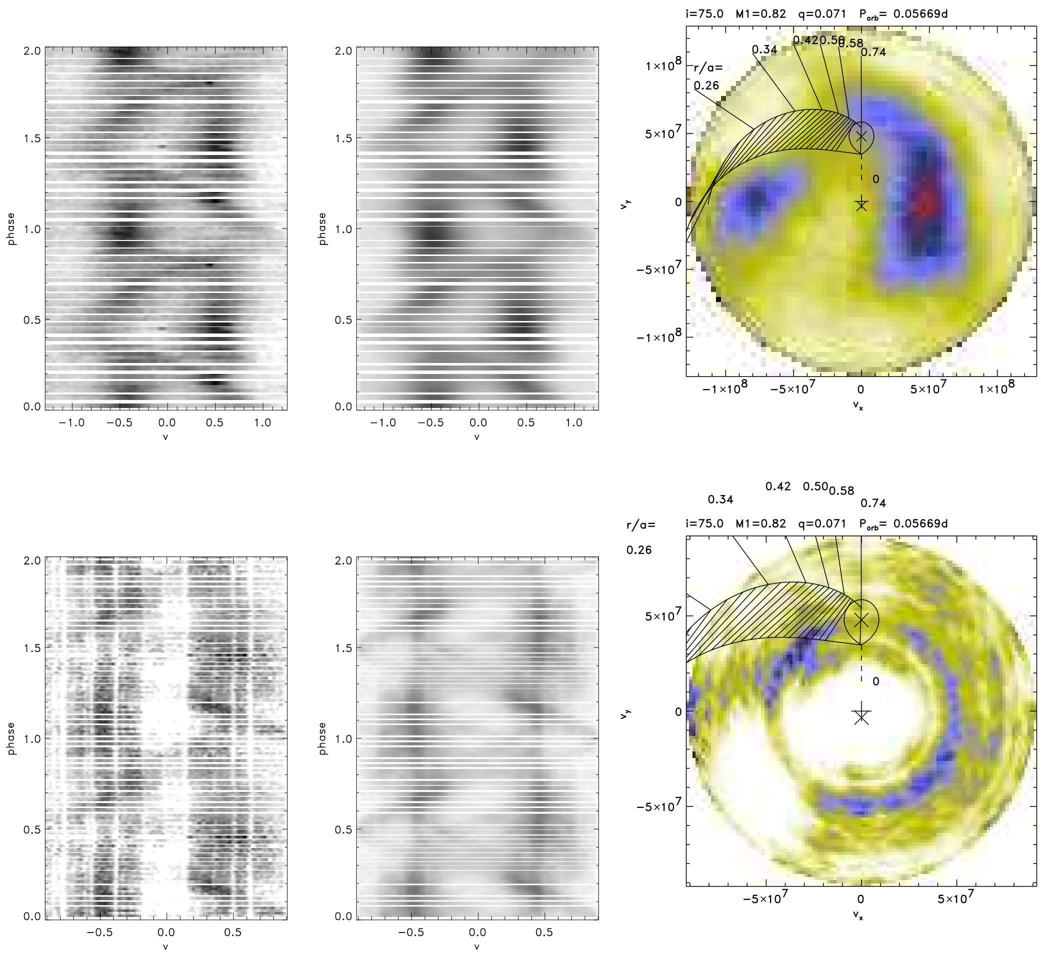

Fig. 3. Doppler maps of HeII (top) and Hα (bottom). Phase-folded spectra are shown in the left column, corresponding Doppler maps are in the right, and spectra reconstructed from the maps are shown in the middle column. Since the (partial) eclipse violates the Doppler mapping assumption of equal visibility at all phases, spectra obtained between -0.05 and 0.05 have been excluded from the reconstruction process. However these parts of the data are included in the spectra shown in Fig. 3 to clarify the change of the trails. The theoretical trajectory of the mass transferring stream are plotted in the Doppler images, together with the Keplerian velocity along the stream path. Bars connecting the two arcs indicate correspondence in physical space, and are annotated with radius (r/a) and the azimuth relative to the primary. The system parameters including gamma velocity are taken from Skidmore et al. (2000).

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